Aurora on Ganymede

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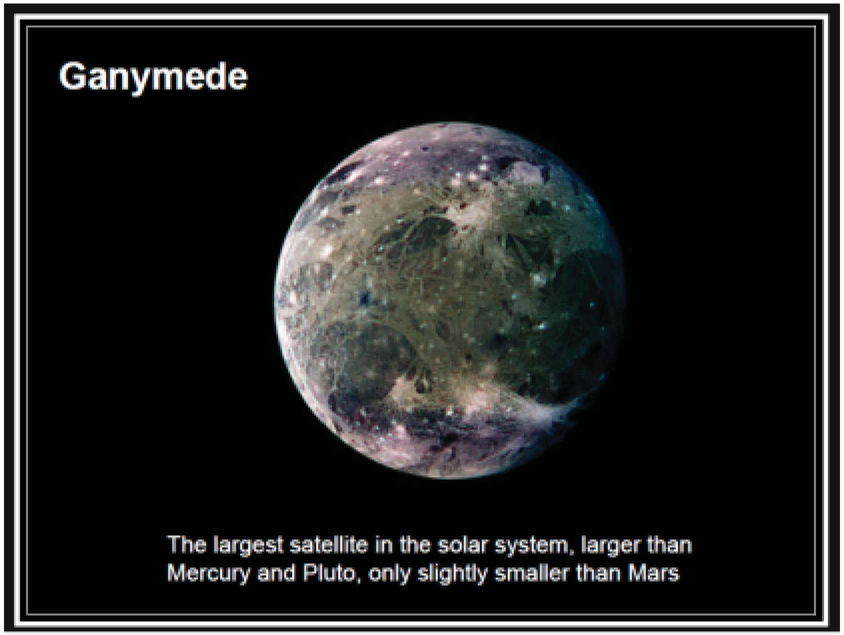
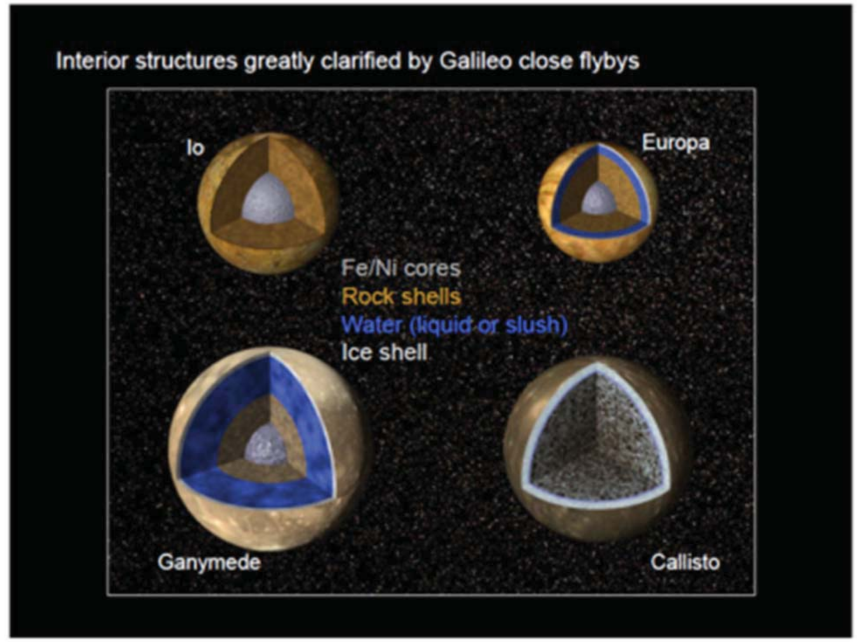
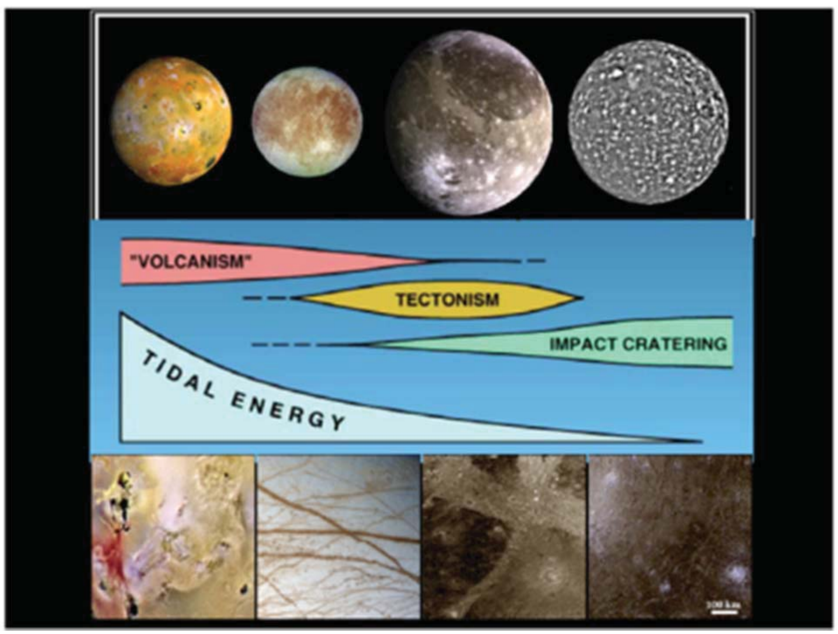
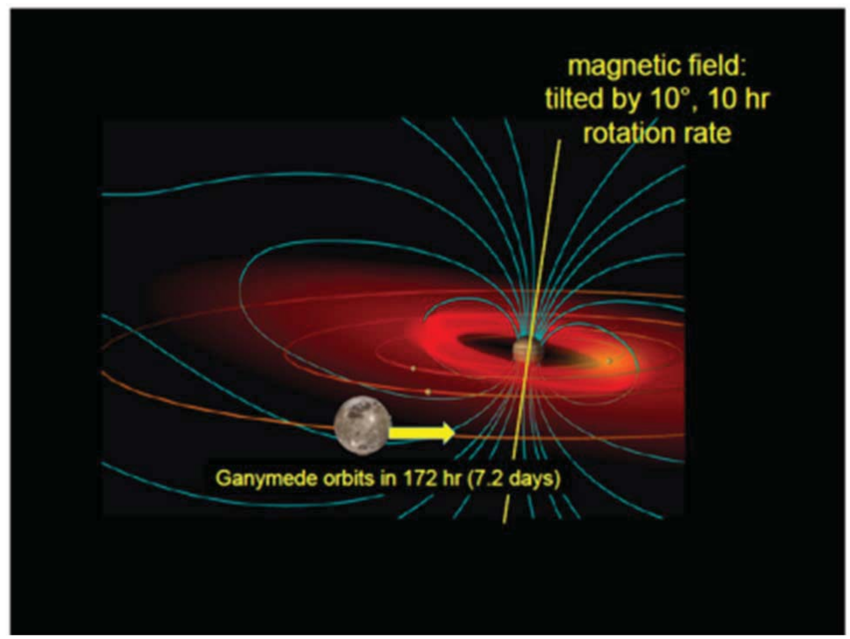

Ganymede
The largest satellite in the solar system, larger than
Mercury and Pluto, only slightly smaller than Mars


Interior structures greatly clarified by Galileo close flybys
Io
Europa
Fe/Ni cores
Rock shells
Water (liquid or slush)
Ice shell
Ganymede
Callisto

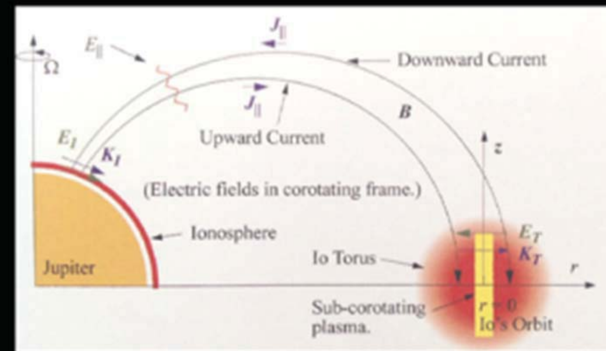

"VOLCANISM"
TECTONISM
IMPACT CRATERING
TIDAL ENERGY


magnetic field:
tilted by 10°, 10 hr
rotation rate
Ganymede orbits in 172 hr (7.2 days)

All the Galilean satellites have tenuous atmospheres and associated ionospheres that exhibit a wide range of properties, including surface pressures ranging from picobar (Europa, Ganymede) to nanobar (Io).

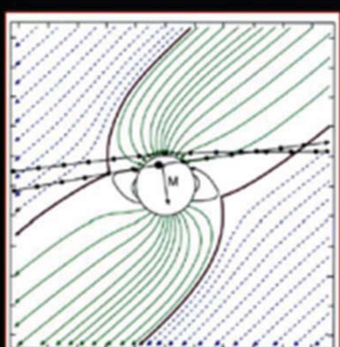
	Io	Europa	Ganymede	Callisto
Primary constituent	SO_2	O_2	O_2	O_2
P_o (nbar)	0.6	7×10^{-4}	7×10^{-4}	0.01-0.1
N (cm^{-2})	2×10^{16}	5×10^{14}	5×10^{14}	$\sim 10^{16}$ O_2 8×10^{14} CO_2
Source	Volcanoes/ sublimation	Sputtering/ sublimation	Sputtering	Sputtering/ meteorites?

Satellites with atmospheres and ionospheres immersed in the strong magnetic field and plasma environment of the Jovian magnetosphere produce a strong electrodynamic interaction between plasma and satellite

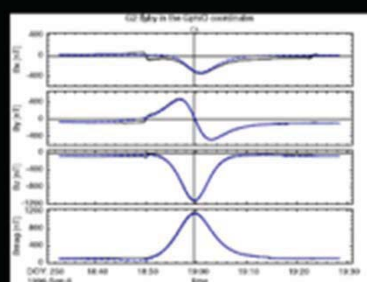


The Galilean satellites are unique because emissions from their atmospheres, produced by this interaction, have been imaged. Each has distinctive auroral emissions that provide a unique signature of the plasma interaction at the satellite.

Galileo discovery of Ganymede magnetic field



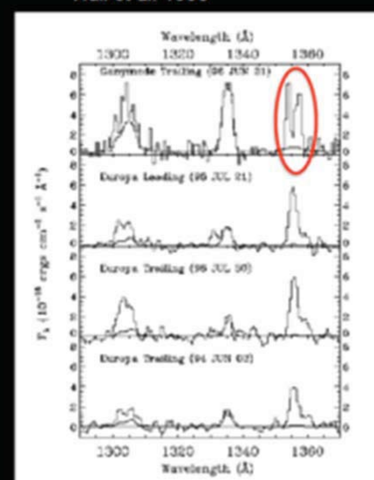
Strong magnetic field and considerable field rotation near Ganymede indicated the perturbations were Ganymede-associated.

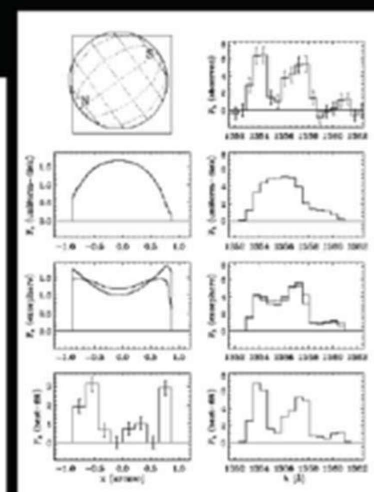


Gurnett et al. 1996
Kivelson et al. 1996

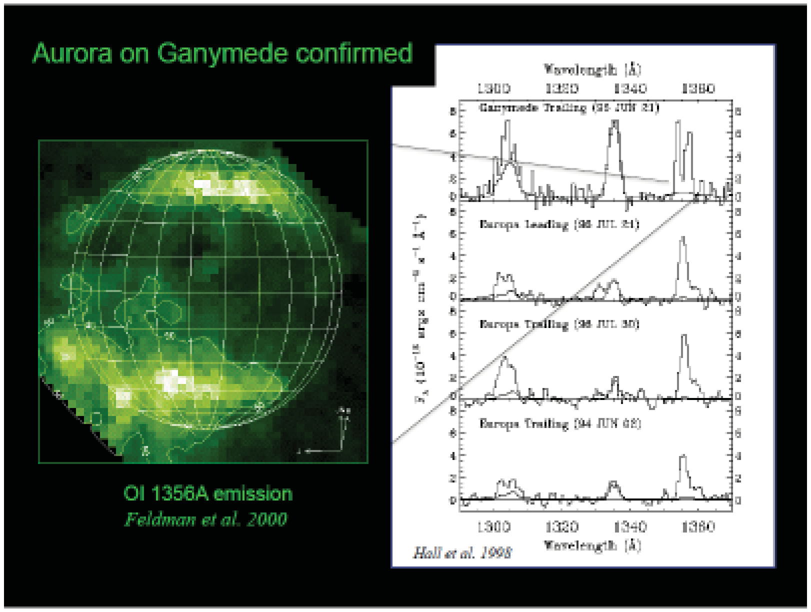
Detection of O_2 atmosphere

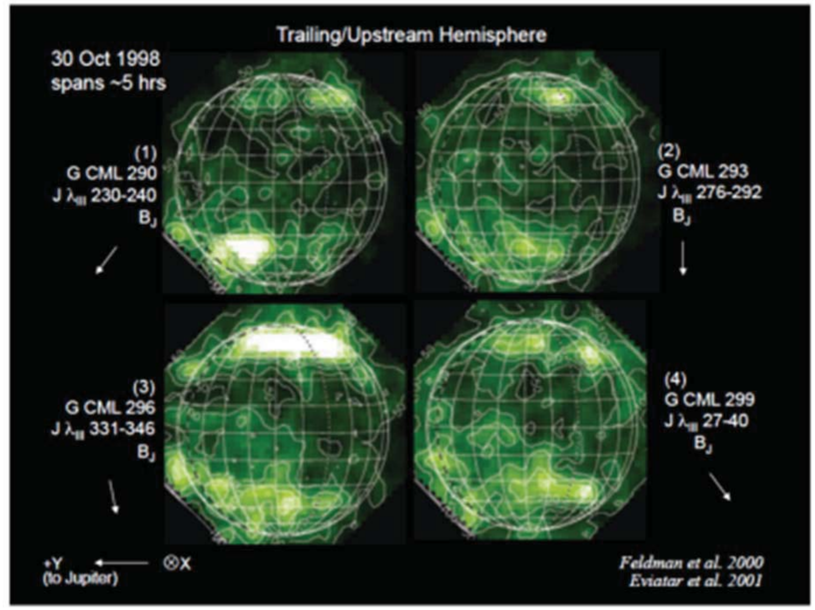
Hall et al. 1998

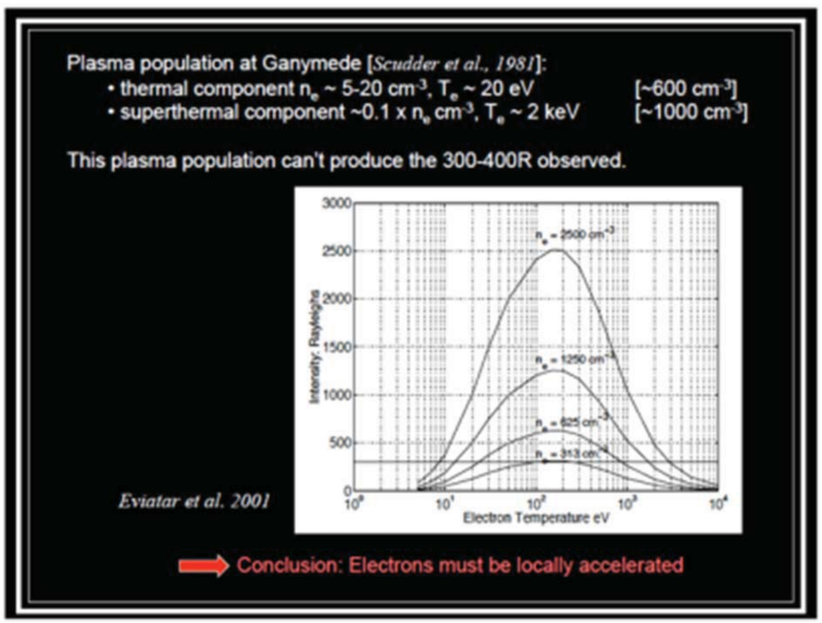


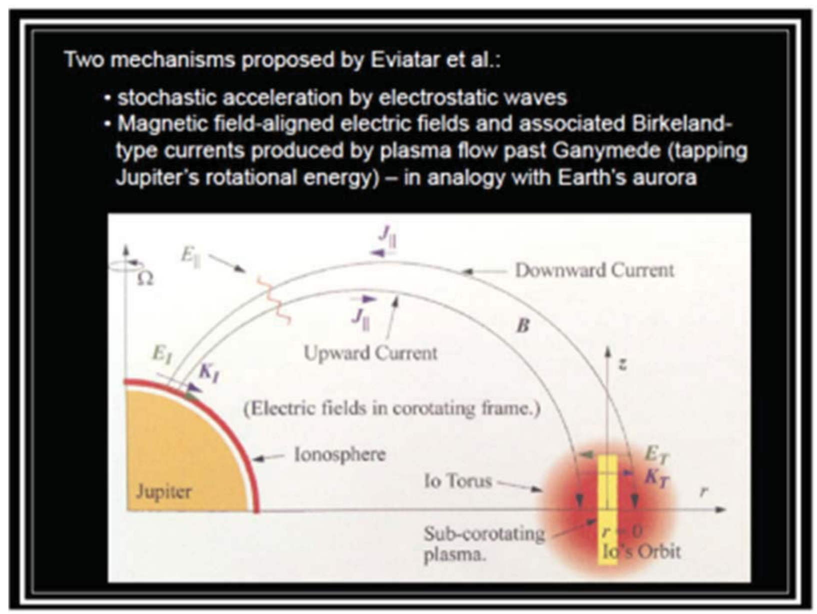


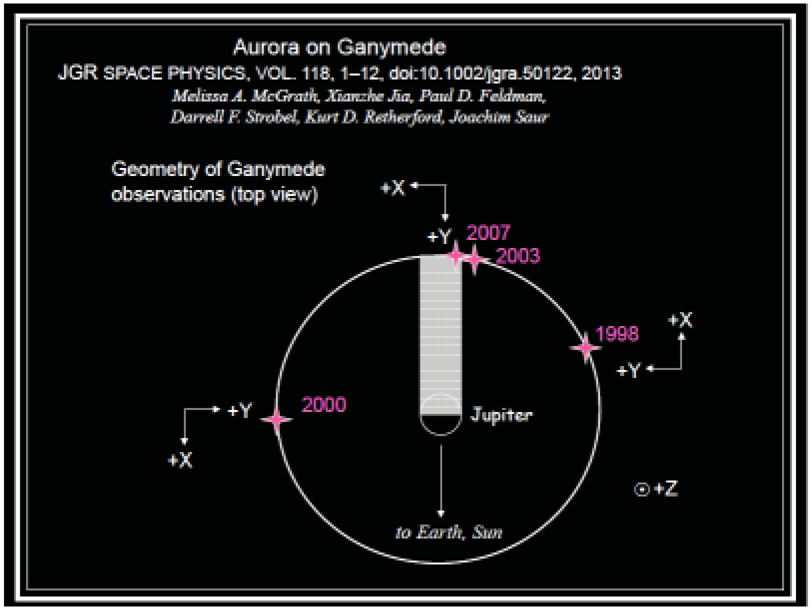
Aurora on Ganymede?

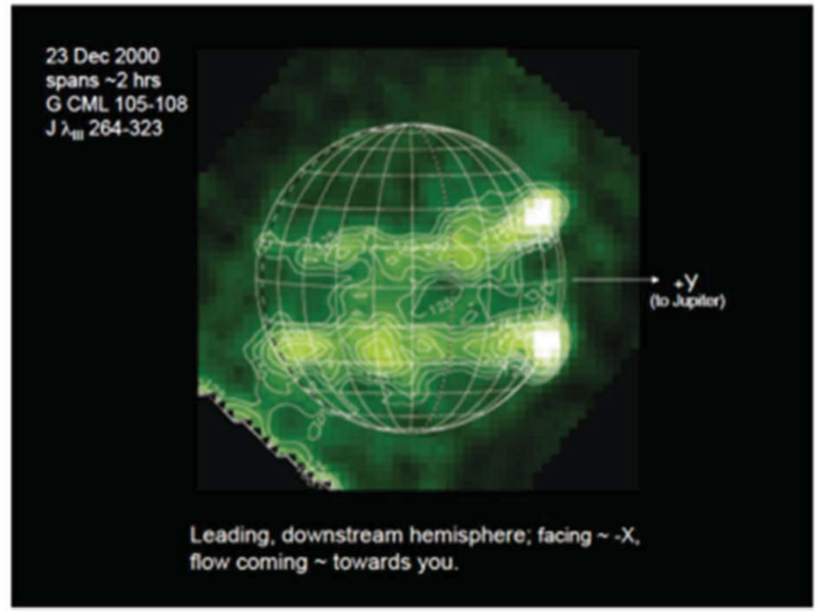

Aurora on Ganymede confirmed
Wavelength (Å)
Ganymede Trailing (98 JUN 21)
Europa Leading (96 JUL 21)
Europa Trailing (96 JUL 30)
Europa Trailing (94 JUN 02)
1300 1320 1340 1360
Wavelength (Å)
Hall et al. 1998
OI 1356A emission
Feldman et al. 2000

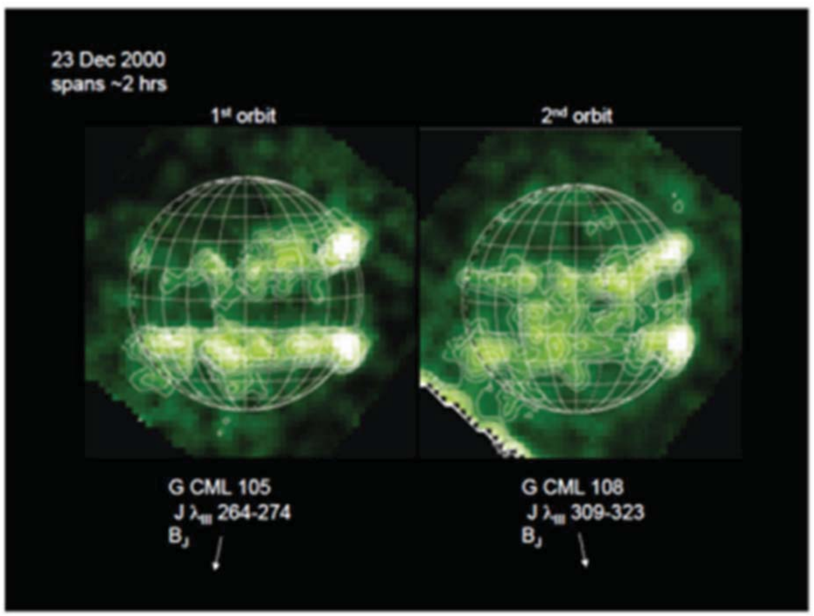

Trailing/Upstream Hemisphere
30 Oct 1998
spans ~5 hrs
(1)
G CML 290
J λIII 230-240
BJ
(2)
G CML 293
J λIII 276-292
BJ
(3)
G CML 296
J λIII 331-346
BJ
(4)
G CML 299
J λIII 27-40
BJ
+Y
(to Jupiter)
⊗X
Feldman et al. 2000
Eviatar et al. 2001


Plasma population at Ganymede [Scudder et al., 1981]:
• thermal component ne ~ 5-20 cm-3, Te ~ 20 eV [~600 cm-3]
• superthermal component ~0.1 x ne cm-3, Te ~ 2 keV [~1000 cm-3]
This plasma population can't produce the 300-400R observed.
ne = 2500 cm-3
ne = 1250 cm-3
ne = 625 cm-3
ne = 313 cm-3
Intensity, Rayleighs
Electron Temperature eV
Eviatar et al. 2001
Conclusion: Electrons must be locally accelerated

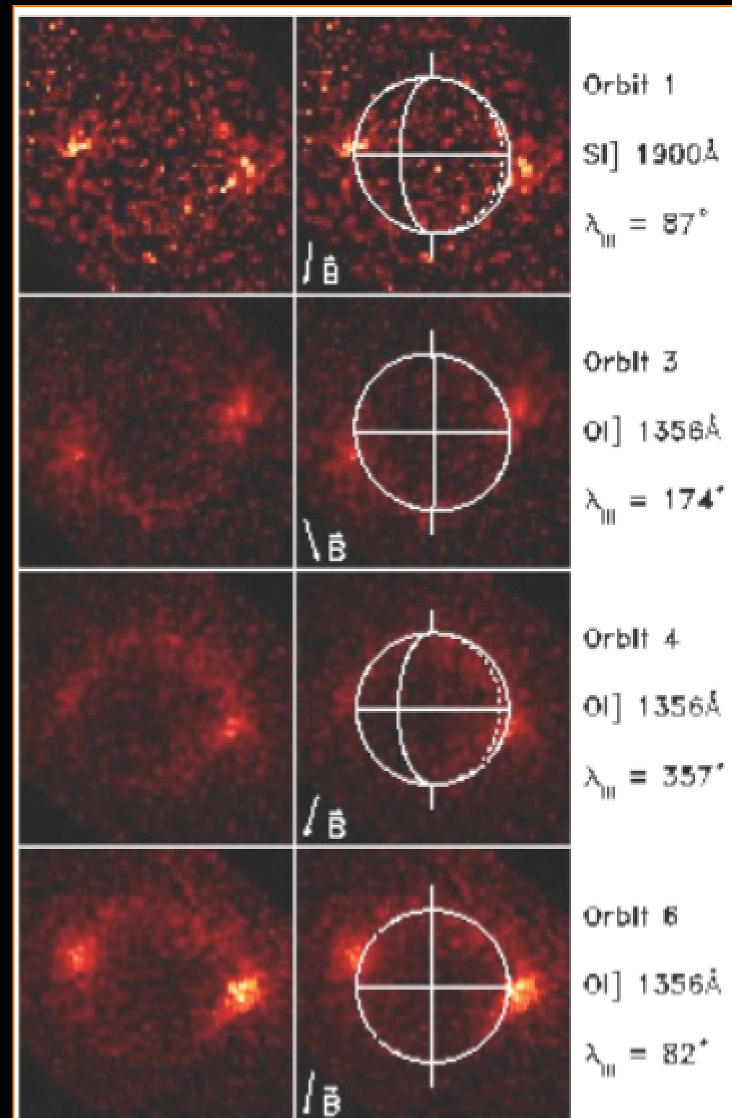

Two mechanisms proposed by Eviatar et al.:
• stochastic acceleration by electrostatic waves
• Magnetic field-aligned electric fields and associated Birkeland-type currents produced by plasma flow past Ganymede (tapping Jupiter's rotational energy) – in analogy with Earth's aurora
Ω
E∥
J∥
Downward Current
Upward Current
B
EI
KI
(Electric fields in corotating frame.)
Ionosphere
Jupiter
Io Torus
ET
KT
Sub-corotating plasma.
Io's Orbit


Aurora on Ganymede
JGR SPACE PHYSICS, VOL. 118, 1–12, doi:10.1002/jgra.50122, 2013
Melissa A. McGrath, Xianzhe Jia, Paul D. Feldman,
Darrell F. Strobel, Kurt D. Retherford, Joachim Saur
Geometry of Ganymede
observations (top view)
+X
+Y
2007
2003
1998
+X
+Y
+Y
2000
Jupiter
+X
+Z
to Earth, Sun

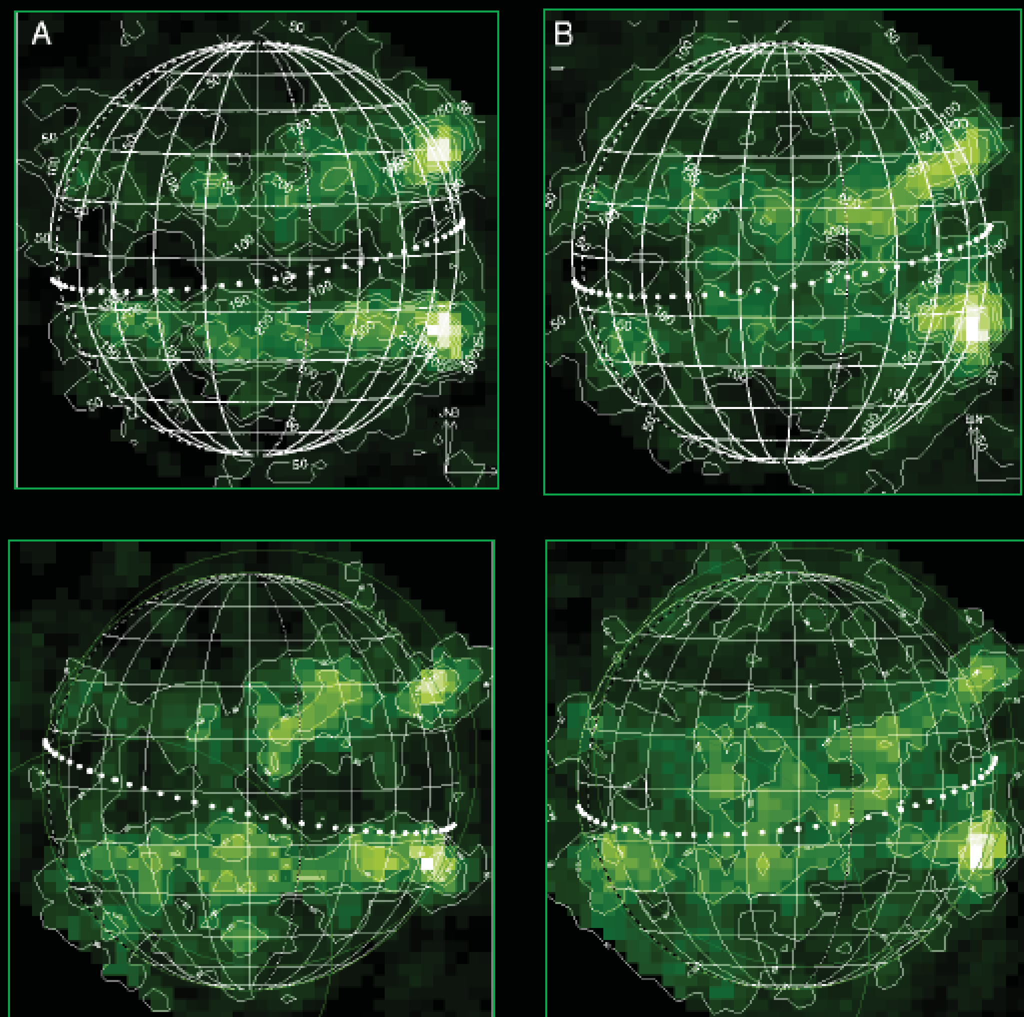

23 Dec 2000
spans ~2 hrs
G CML 105-108
J λ_{III} 264-323
+Y
(to Jupiter)
Leading, downstream hemisphere; facing ~ -X,
flow coming ~ towards you.


23 Dec 2000
spans ~2 hrs
1st orbit
2nd orbit
G CML 105
J λ_{III} 264-274
B_J
G CML 108
J λ_{III} 309-323
B_J

At Io, the auroral emission has a very different morphology: equatorial bright spots that rock with changing Jupiter B field orientation



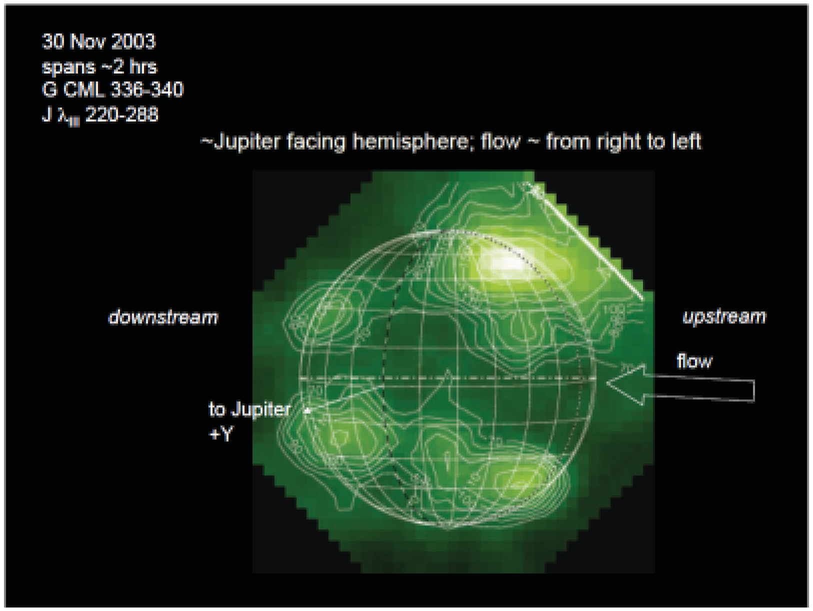
Roesler et al. 1999

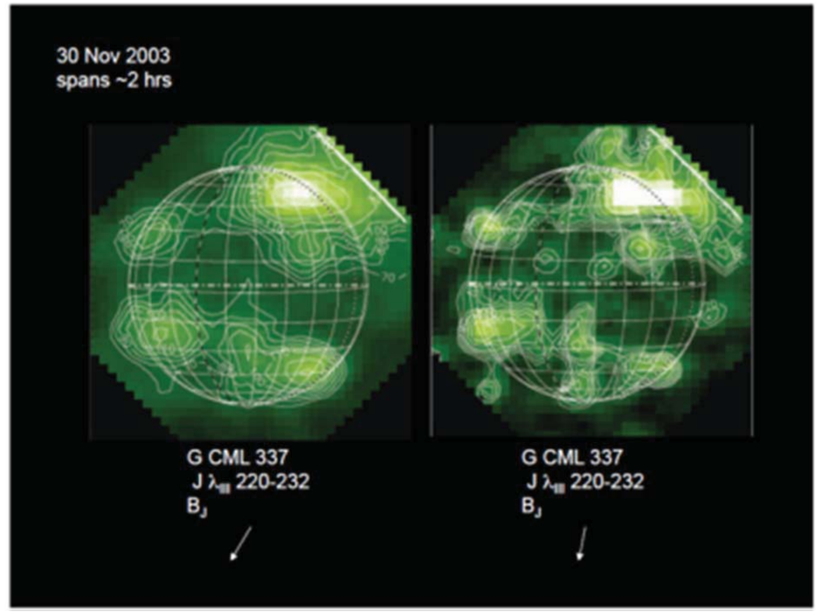


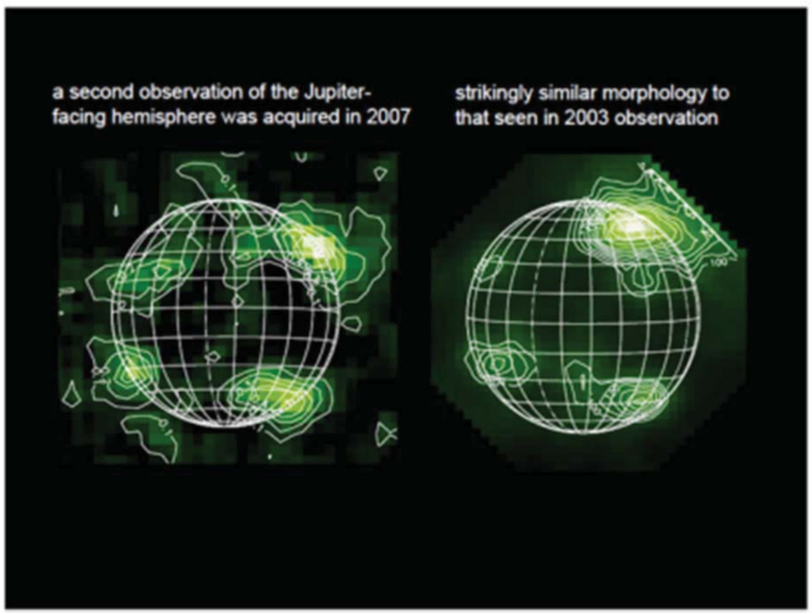
Ganymede B field equator superposed

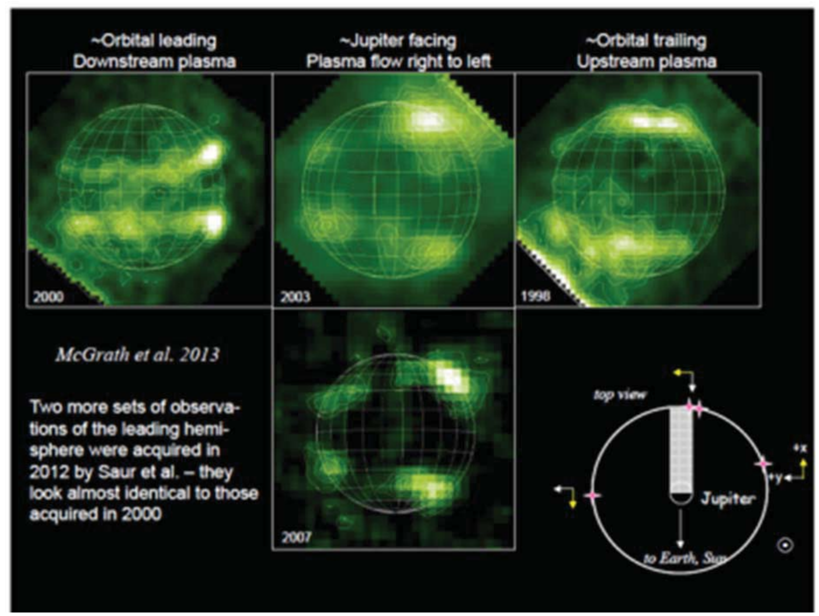
Jupiter B field equator superposed

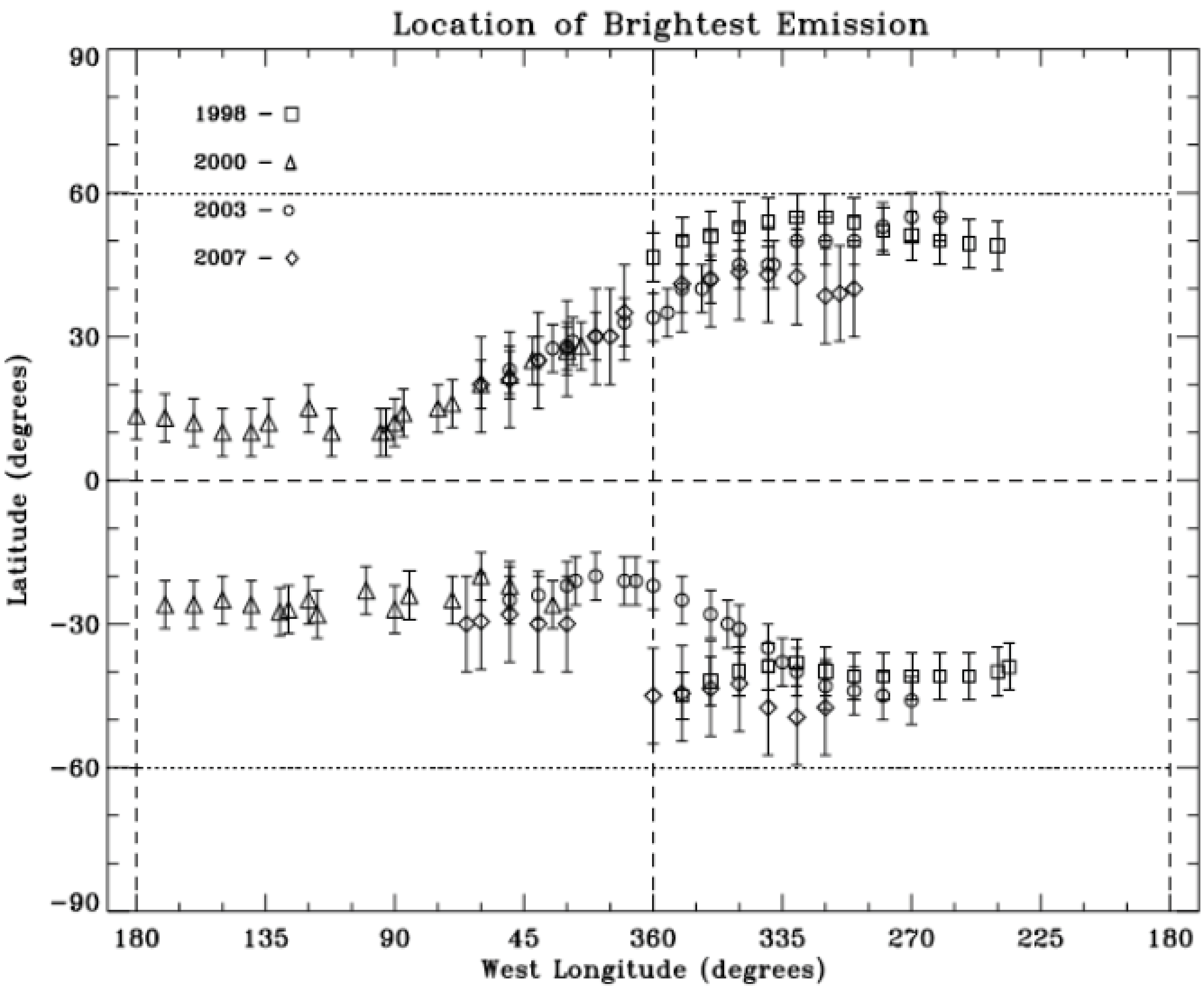
Conclusion: Ganymede's auroral oval does not rock like Io's spots


30 Nov 2003
spans ~2 hrs
G CML 336-340
J λIII 220-288
~Jupiter facing hemisphere; flow ~ from right to left
downstream
upstream
flow
to Jupiter
+Y

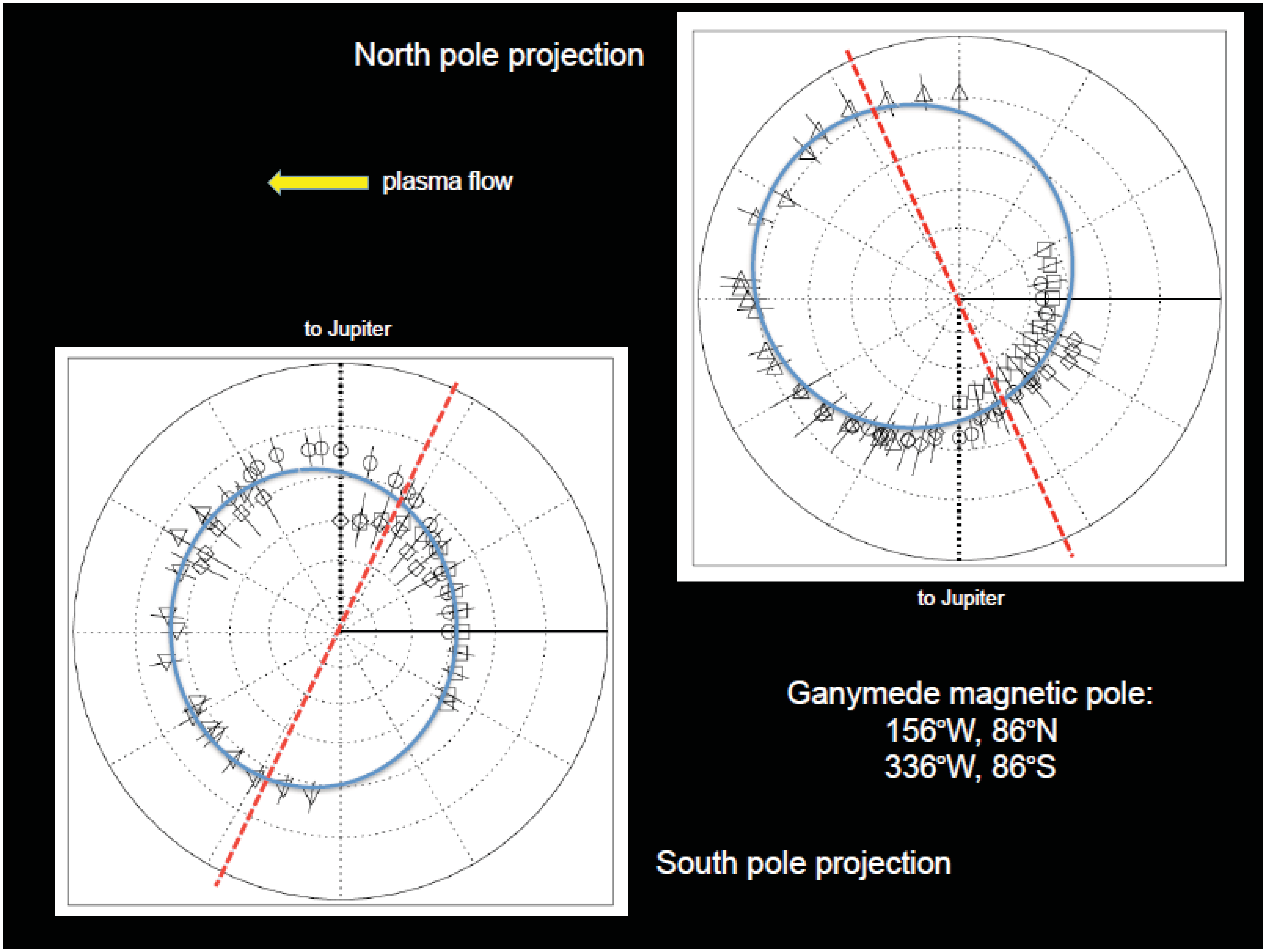

30 Nov 2003
spans ~2 hrs
G CML 337
J λIII 220-232
BJ
G CML 337
J λIII 220-232
BJ


a second observation of the Jupiter-facing hemisphere was acquired in 2007
strikingly similar morphology to that seen in 2003 observation


~Orbital leading
Downstream plasma
~Jupiter facing
Plasma flow right to left
~Orbital trailing
Upstream plasma
2000
2003
1998
McGrath et al. 2013
Two more sets of observations of the leading hemisphere were acquired in 2012 by Saur et al. – they look almost identical to those acquired in 2000
2007
top view
Jupiter
to Earth, Sun



Location of Brightest Emission
1998 – □
2000 – △
2003 – ○
2007 – ◇
Latitude (degrees)
West Longitude (degrees)
90
60
30
0
−30
−60
−90
180
135
90
45
360
335
270
225
180

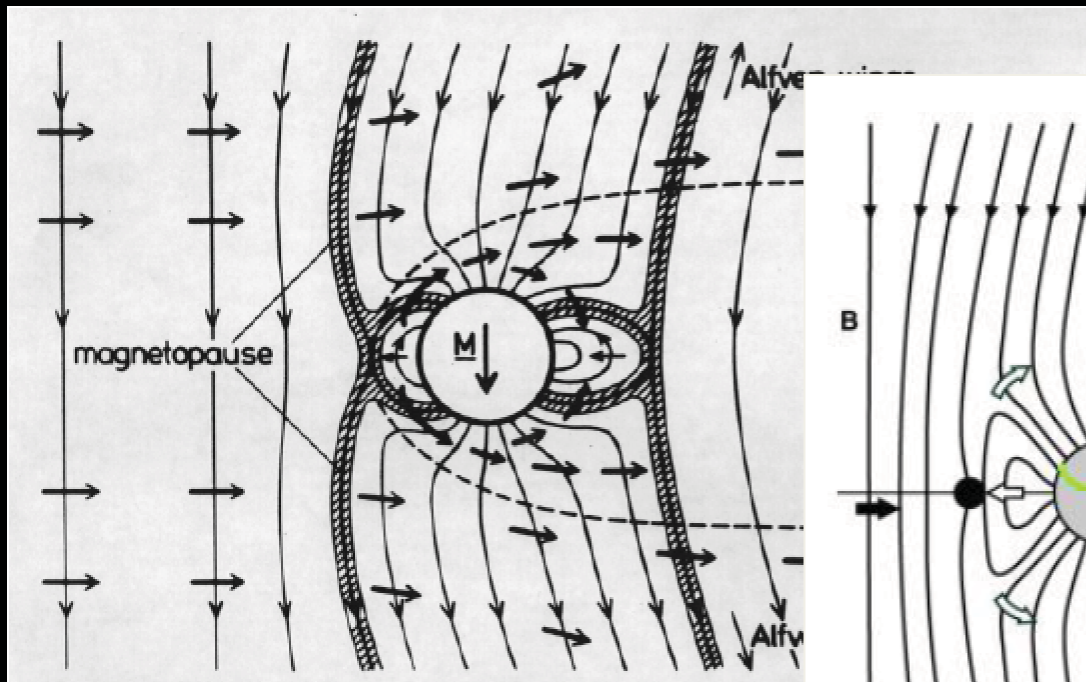

North pole projection
plasma flow
to Jupiter
to Jupiter
Ganymede magnetic pole:
156°W, 86°N
336°W, 86°S
South pole projection

Summary of observed characteristics

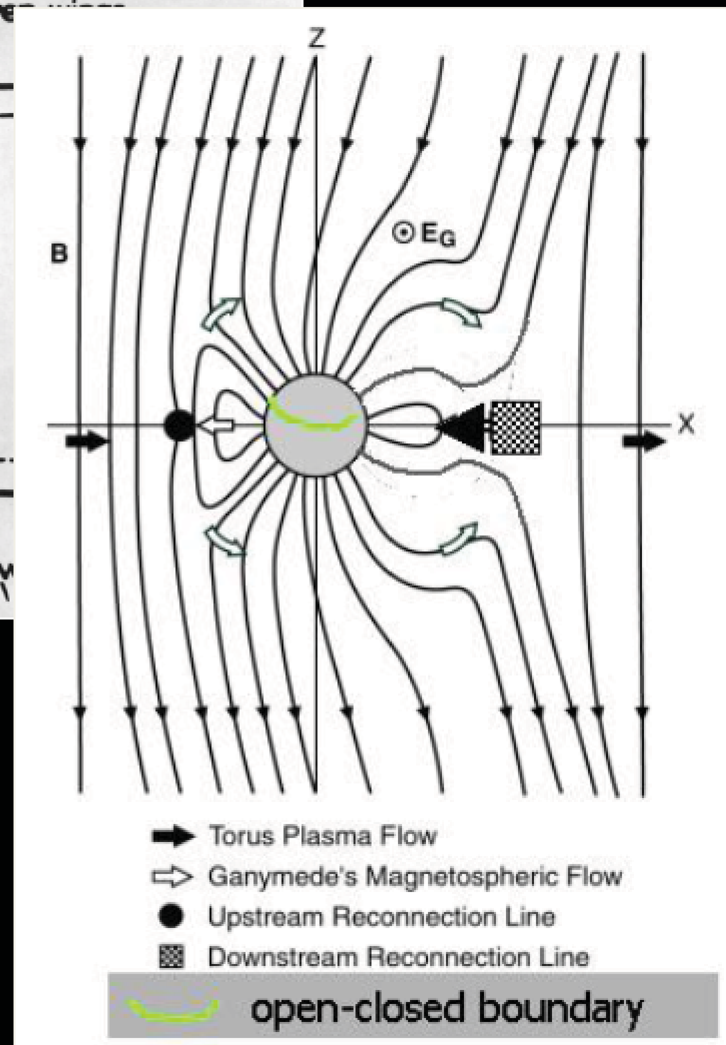
- The overall emission pattern is relatively stable with time.
- In the downstream hemisphere, the emission extends to significantly lower latitude in the northern hemisphere than the southern hemisphere.
- The opposite is true in the upstream hemisphere: emission is at higher latitude in the northern hemisphere than the southern hemisphere.
- The emission is not symmetric about either pole.
- The emission is not symmetric about the equator.
- The auroral oval is is stretched in the downstream direction, more so in the N than the S.
- The auroral oval is not symmetric about the plasma flow direction. It appears to be roughly aligned with Ganymede's magnetic axis, especially in the north.
- Emission is always brightest near the NW (dusk) limb, followed by SW limb, then SE limb, then NE limb

Comparison with Models

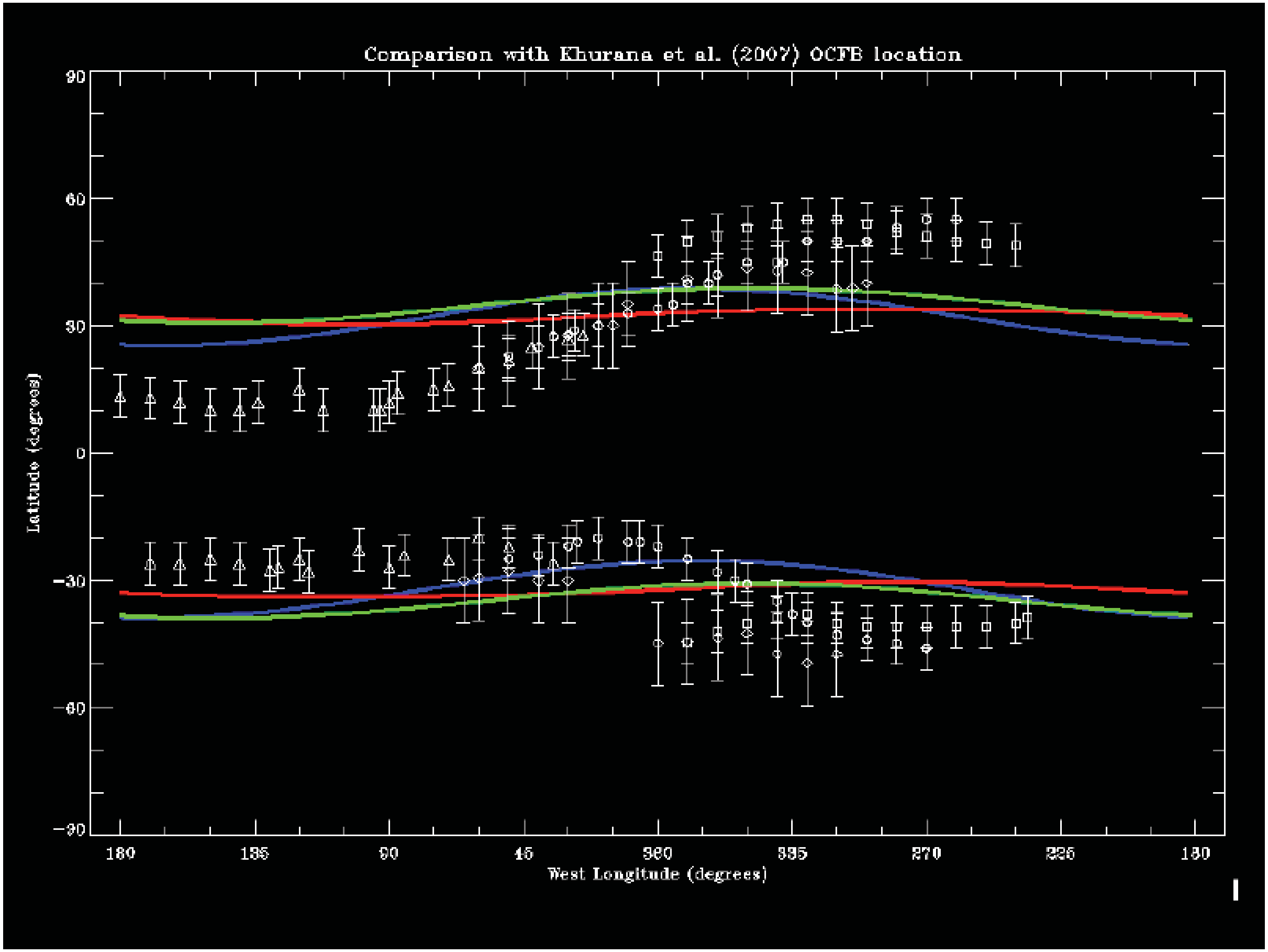
- One proposed mechanism: Electrons accelerated by field aligned potentials at the boundary between Ganymede's open and closed field magnetic lines produce the auroral emission
- I will show you comparison between location of the open-closed field line boundary (OCFB) and the location of the auroral emission for several different models:
  - Khurana et al. (2007): vacuum superposition of Ganymede & Jupiter magnetic fields
  - Koop & Ip (2002): resistive MHD model
  - Jia et al. (2008, 2009): global 3-d single-fluid MHD model
- For all comparisons I will show models where Ganymede is ABOVE (in red), IN (in green), and BELOW (in blue) the plasma sheet



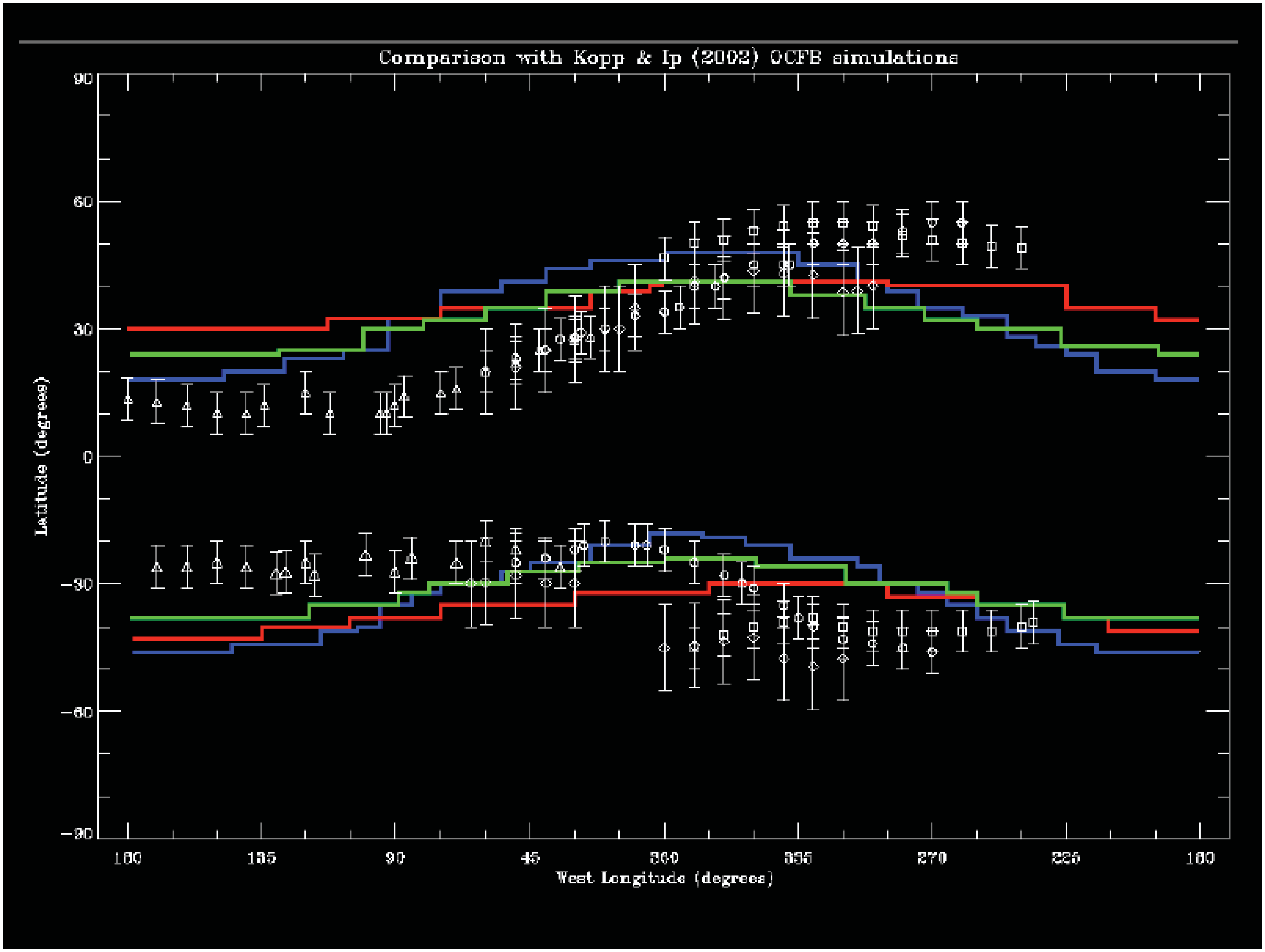
Neubauer 1998



Kivelson 2001

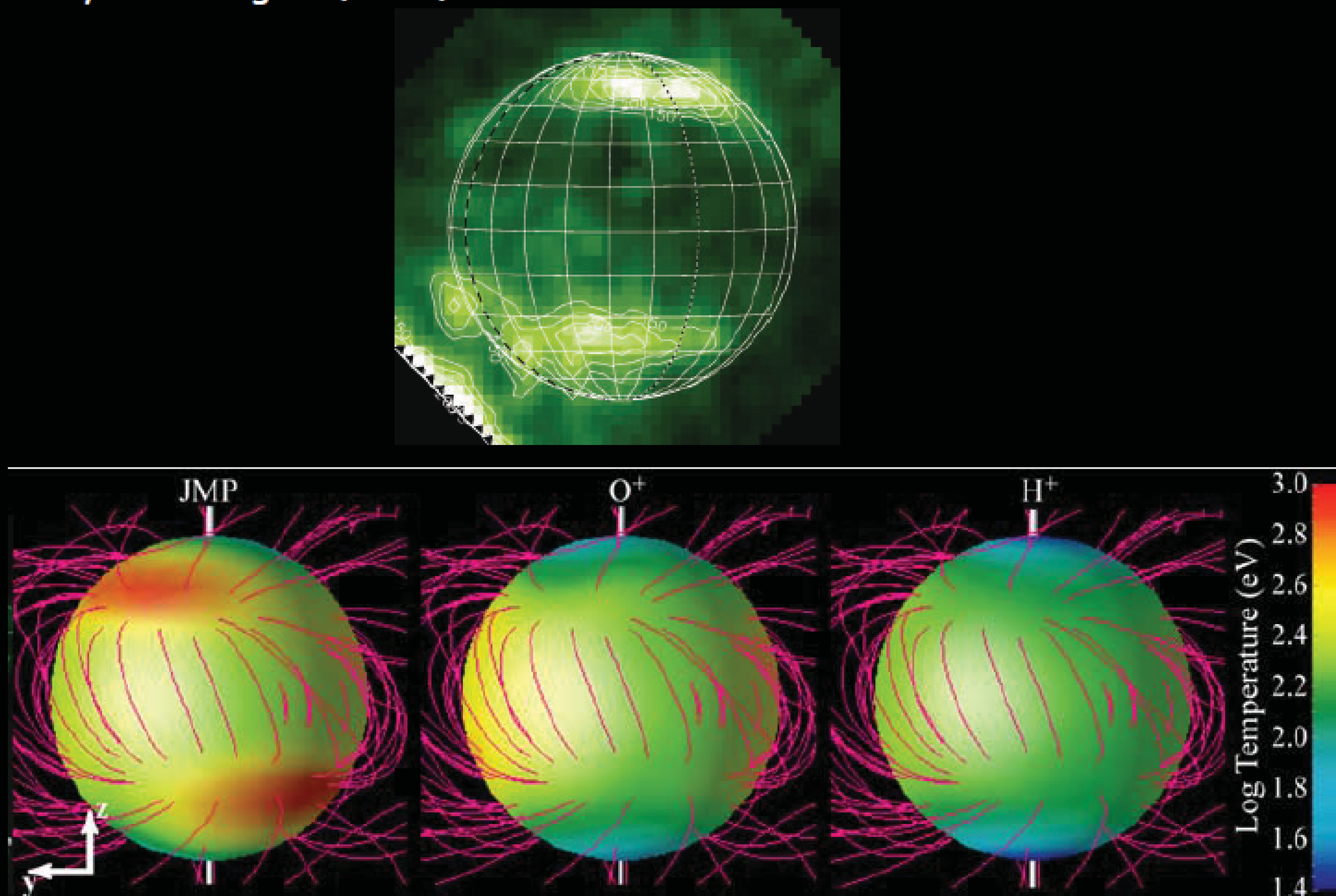


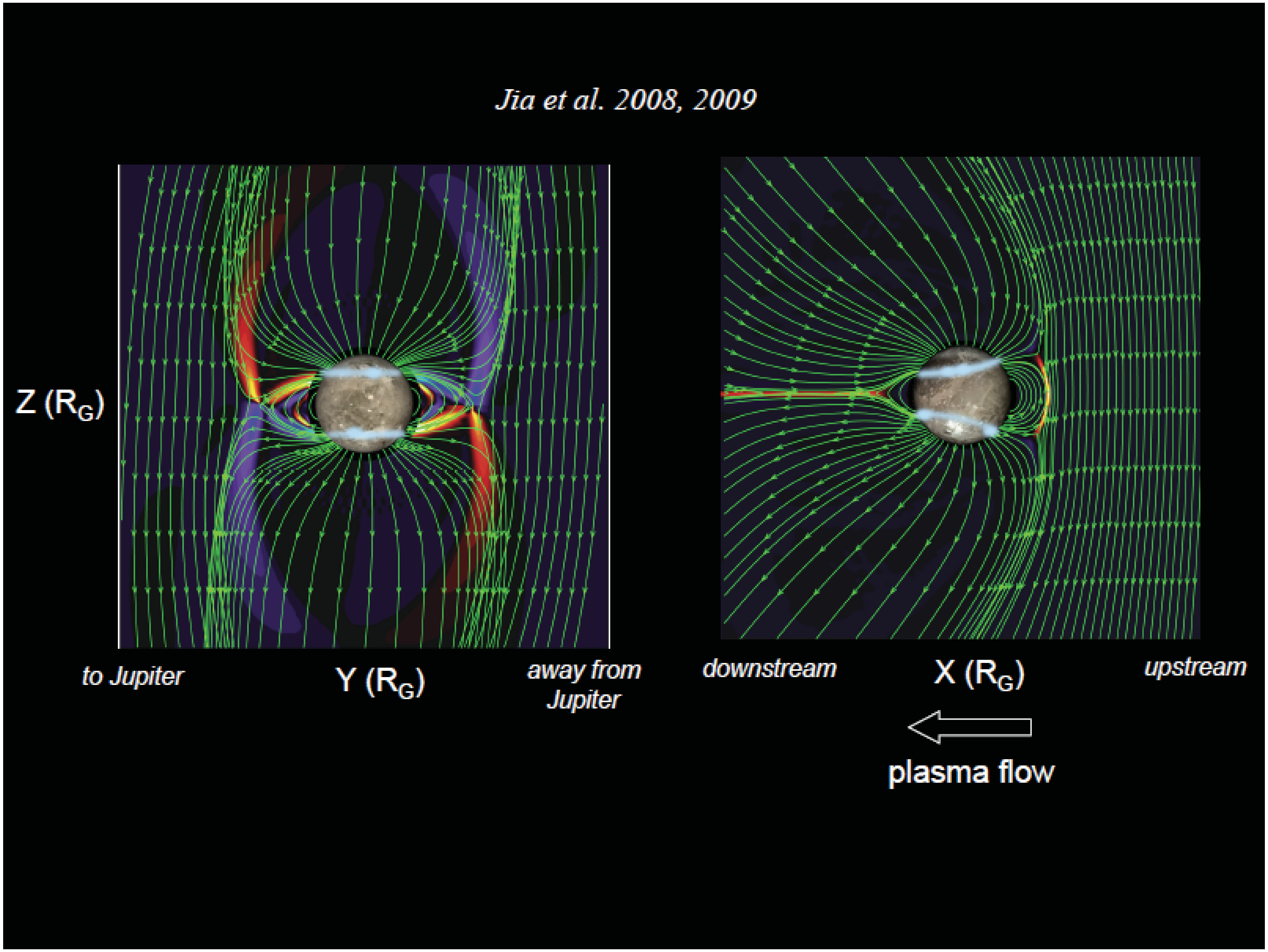
Comparison with Khurana et al. (2007) OCFB location
Latitude (degrees)
West Longitude (degrees)
90
60
30
0
-30
-60
-90
180
135
90
45
360
315
270
225
180

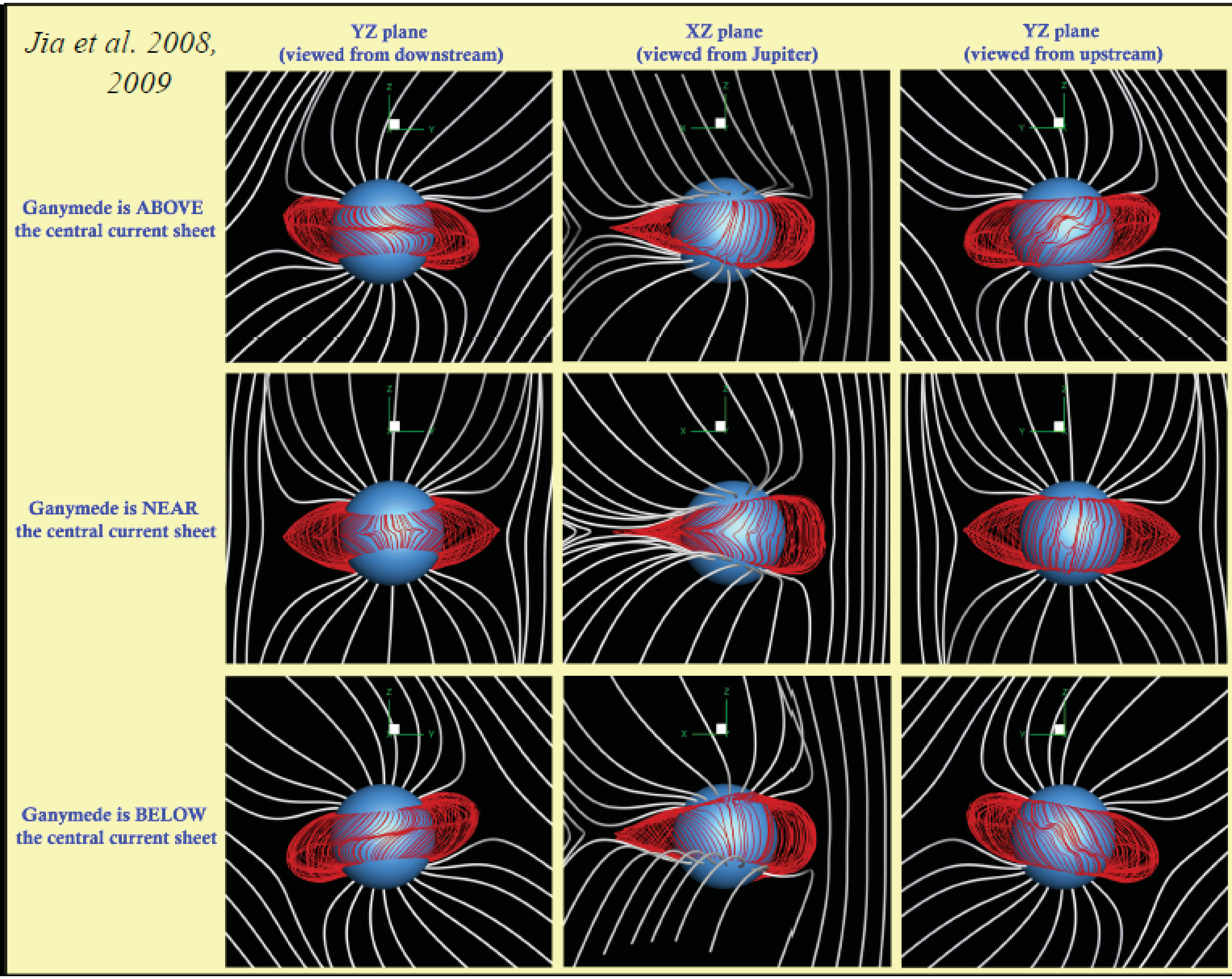


Comparison with Kopp & Ip (2002) OCFB simulations
Latitude (degrees)
West Longitude (degrees)
90
60
30
0
−30
−60
−90
180
135
90
45
360
315
270
225
180

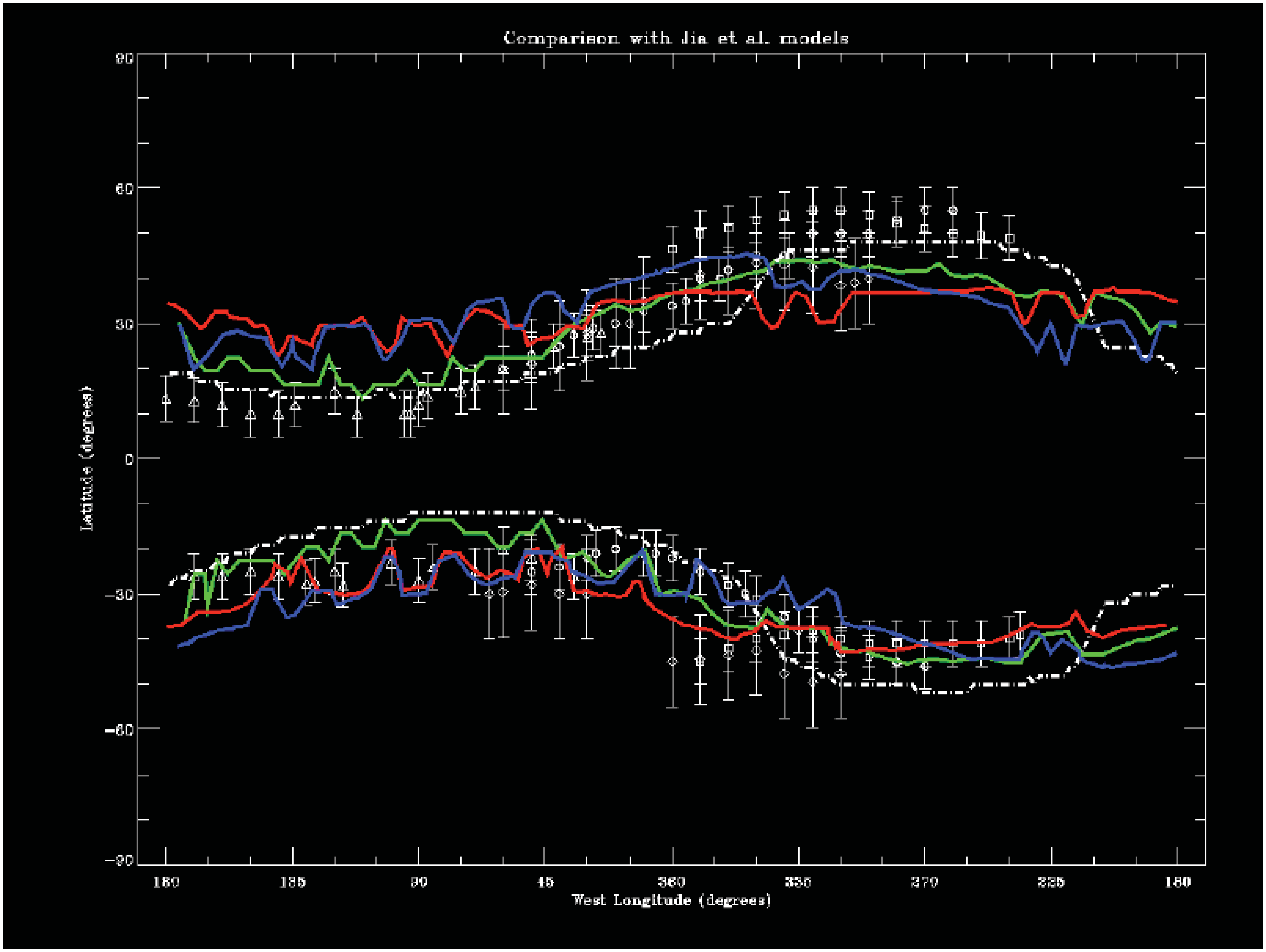
Paty and Winglee (2004)




Jia et al. 2008, 2009
Z (R_G)
to Jupiter
Y (R_G)
away from Jupiter
downstream
X (R_G)
upstream
plasma flow

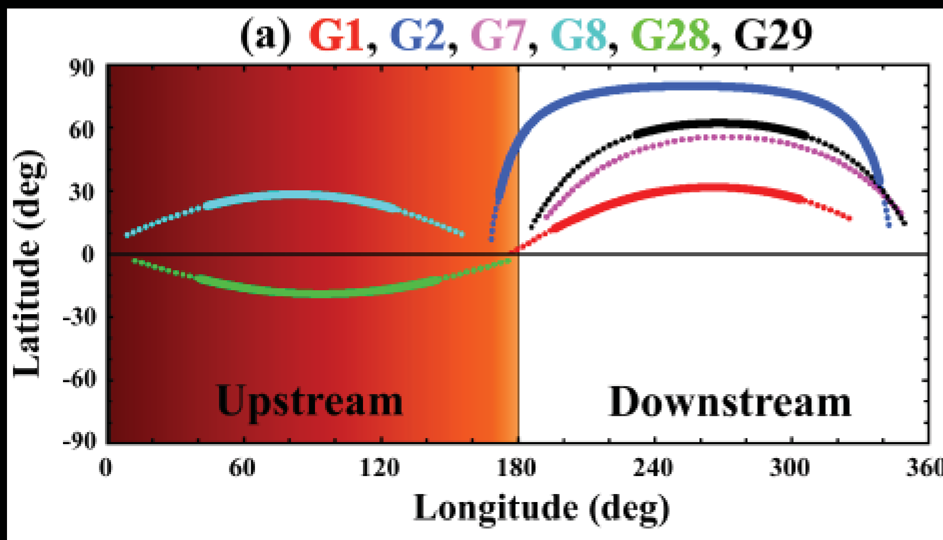


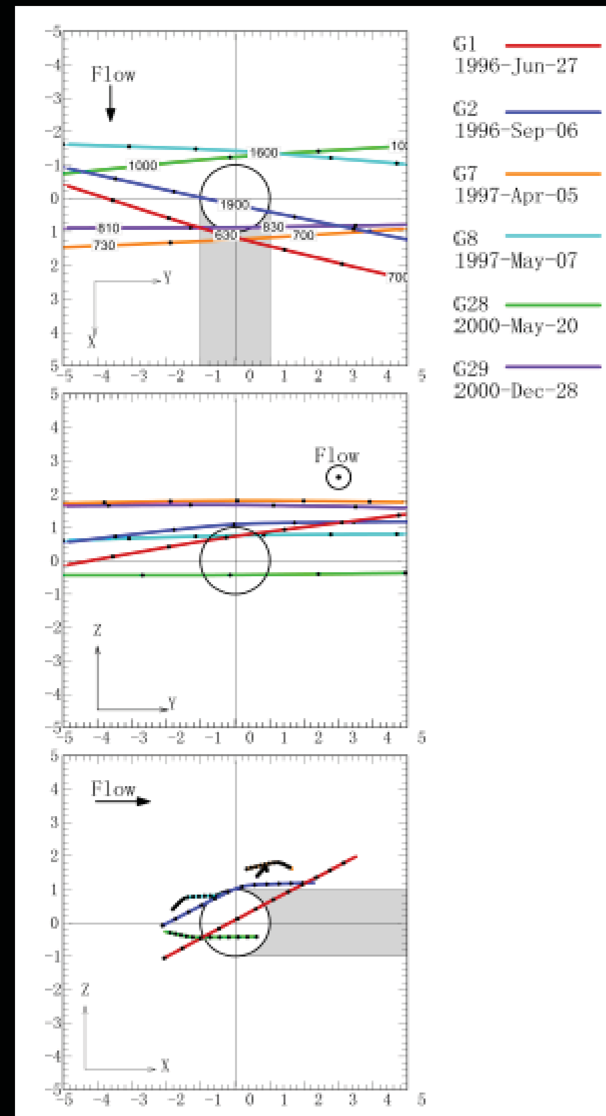
Jia et al. 2008, 2009
YZ plane
(viewed from downstream)
XZ plane
(viewed from Jupiter)
YZ plane
(viewed from upstream)
Ganymede is ABOVE the central current sheet
Ganymede is NEAR the central current sheet
Ganymede is BELOW the central current sheet



Comparison with Jia et al. models
Latitude (degrees)
West Longitude (degrees)
90
60
30
0
-30
-60
-90
180
135
90
45
360
315
270
225
180

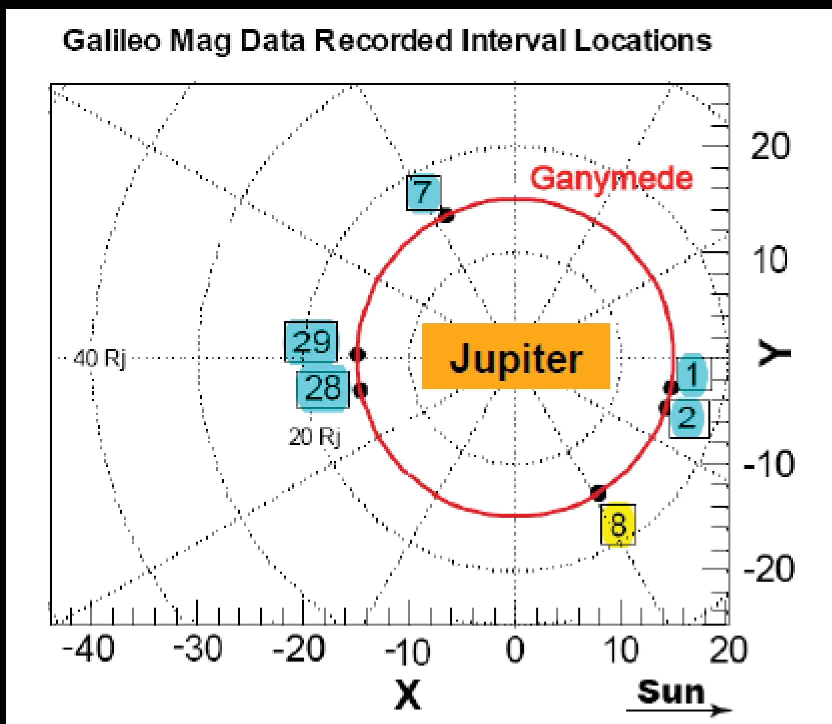
Locations of Galileo's six close encounters with Ganymede

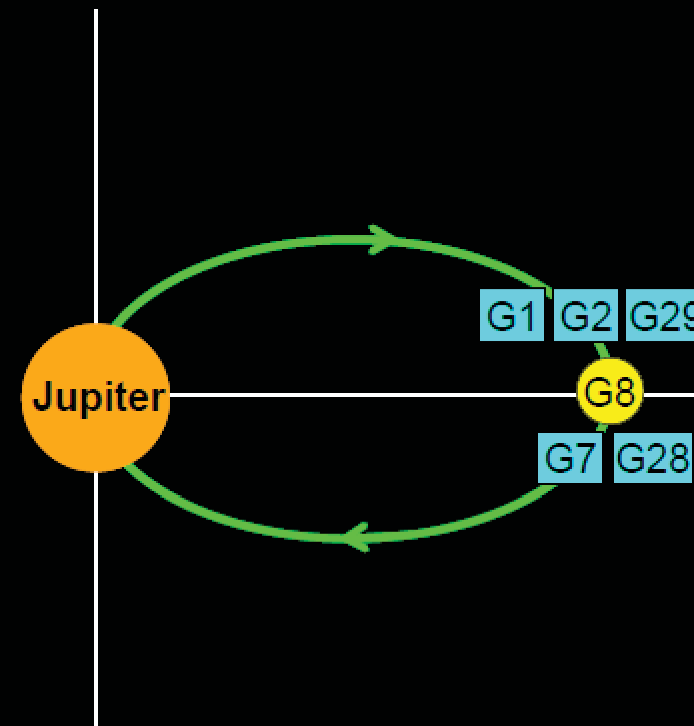




Jia et al. 2009

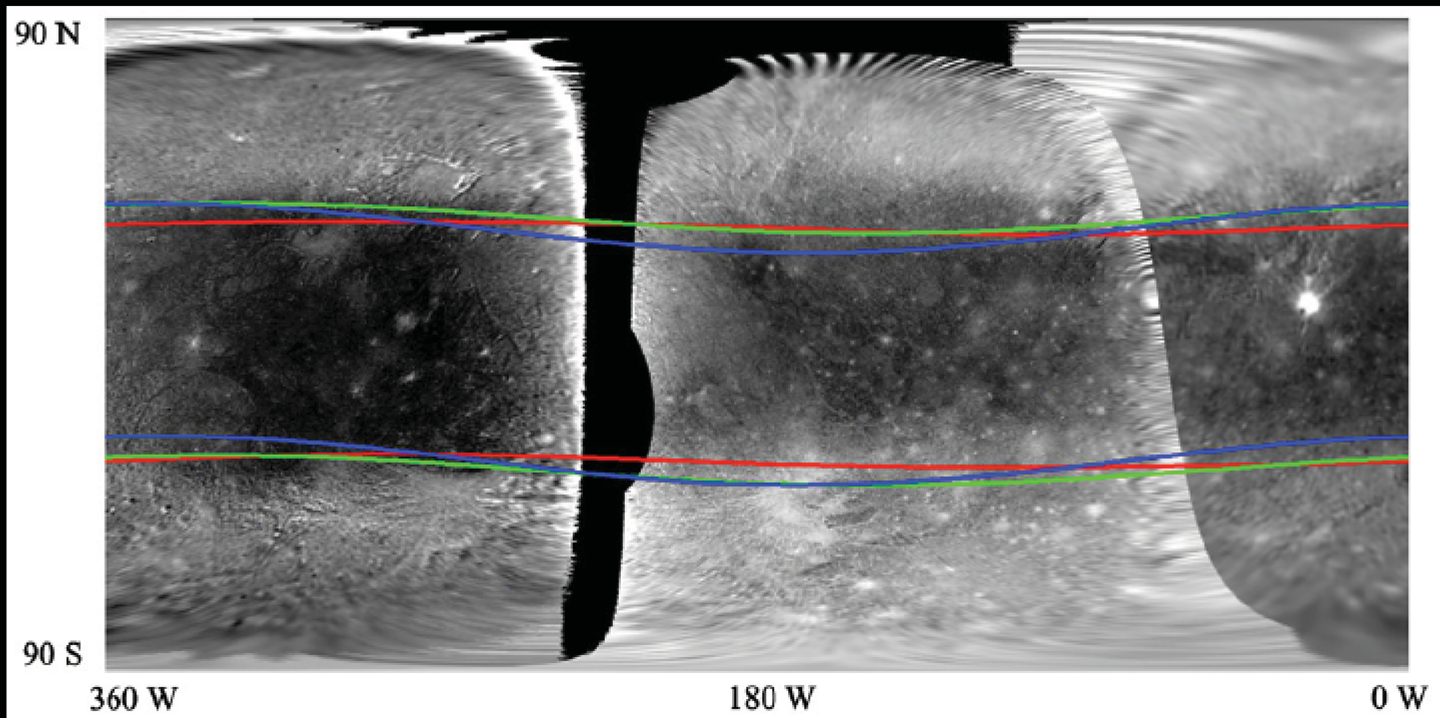
The six close encounters occurred in different local time sectors in Jupiter's magnetosphere and at different locations relative to the Jovian plasma sheet.



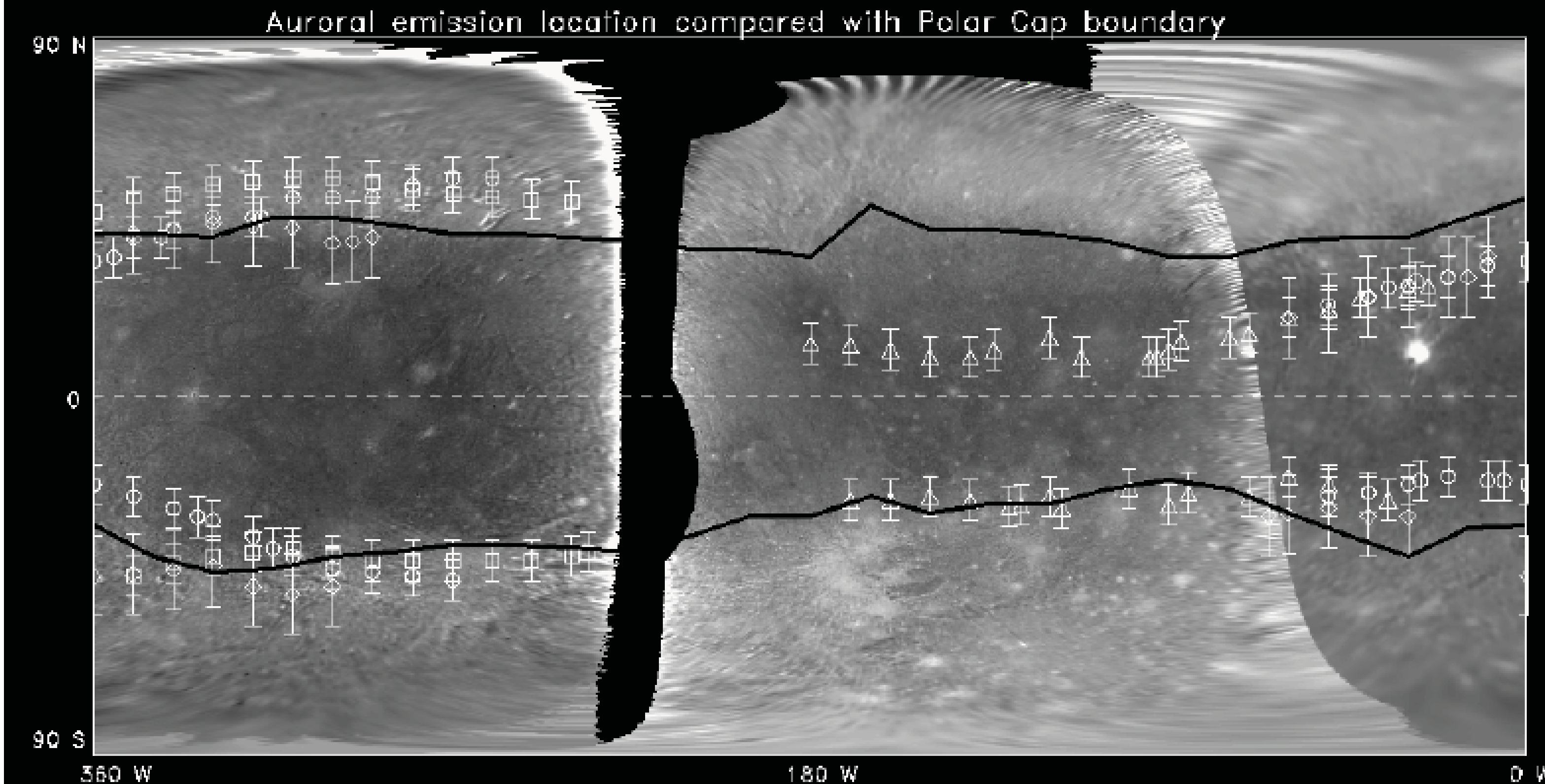


Ganymede has visibly brighter, bluer polar caps

Based on the apparently close correspondence between the OCFB of the Khurana et al. (2009) static superposition model with the polar cap boundary, they concluded that particle bombardment of the poles is the cause of the bright polar caps.



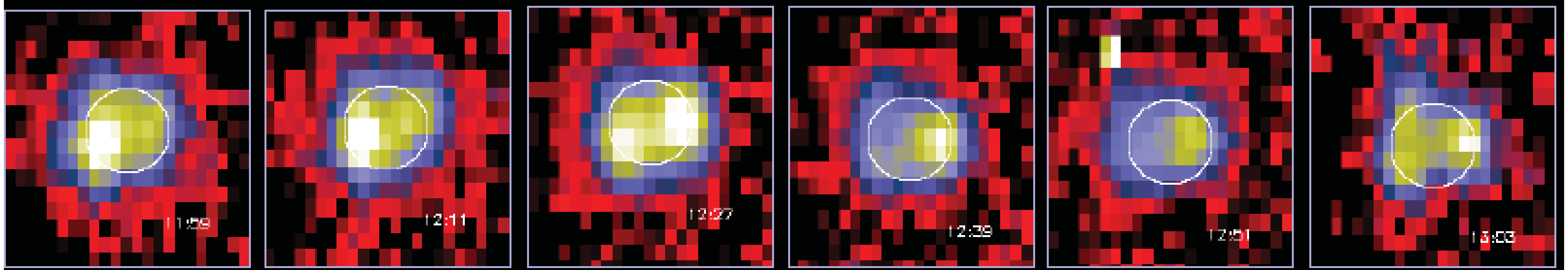
However, I just showed you the close correspondence between the OCFB of the Jia et al. model and auroral emission. Khurana model does not account for the interaction between Jovian plasma and Ganymede.

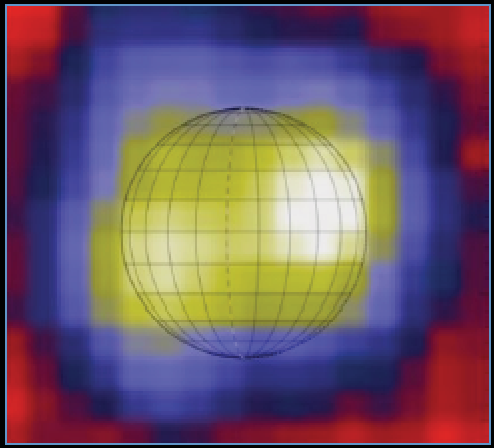


If the auroral emission corresponds to the OCFB, then neither the OCFB nor the auroral emission match the location of the polar cap boundary well in the northern hemisphere especially from 0° – 180° W longitude.

Unpublished Keck observation of *Ganymede* in eclipse (Jupiter-facing hemisphere – same as 2003 and 2007 UV observations) in oxygen 630 nm emission by Mike Brown:

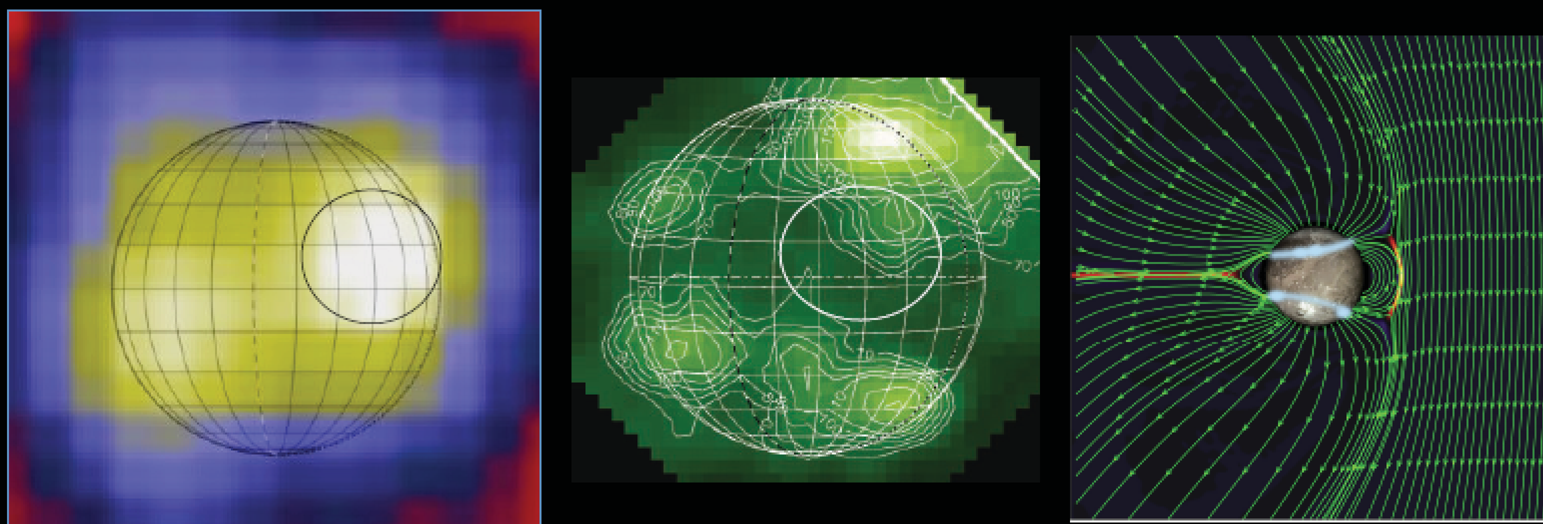
- visible O emission is not at the poles, it is near the equator
- significant short-term variability





Composite spans ~ 1 hr, *G* CML 351, J λ_{III} 69-106

Comparison between visible and UV, almost the same (Jupiter-facing) hemisphere:



Jupiter facing hemisphere, plasma flow from right to left

Summary

- Ganymede has a stable, well-defined pattern of auroral emission: higher latitude on the upstream hemisphere, lower latitude on the downstream hemisphere. The northern oval is bigger than the southern oval.
- The emission pattern is reasonably well matched by the OCFB in the MHD models of Jia et al.
- Puzzling emission morphology has been observed in visible aurora that is inconsistent with the UV morphology.